
The Extended Emission of Ultracompact HII Regions: An Overview and New Observations

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Summary. ⁶

Ultracompact (UC) HII regions with Extended Emission (EE) are classical UC HII regions associated with much larger ($>1'$) structures of ionized gas. The efforts to investigate, detect, and understand if the EE is physically related to the UC emission are few. If they are related, our understanding of UC HII regions may be affected (e.g., in the estimation of ionizing UV photons). Here we present a brief overview of UC HII regions with EE (UC HII+EE) including our most recent effort aimed at searching for UC HII regions associated with extended emission.

1 Introduction

Ultracompact (UC) HII regions are small (size ≤ 0.1 pc), dense ($\geq 10^4$ cm $^{-3}$), photoionized hydrogen regions with high emission measure ($\geq 10^7$ pc cm $^{-6}$), surrounding recently formed ionizing OB type stars (e.g. Fig. 1a). These characteristics were observationally confirmed by [1] and [2], and more recent reviews are presented by [3] and [4]. The study of UC HII regions began in 1967 via interferometric observations of compact HII regions (see [5] for a summary). Because UC HII regions are generally surrounded by a natal dust ‘cocoon’, radio–continuum (RC) and infrared (IR) observations are needed to

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study them. In the RC, the first VLA surveys (e.g., [1], [2]) were made at 2 and 6 cm in configurations A and B, supplying arc-sec resolutions and sensitivities to structures up to $10\text{--}20''$. The IR counterparts were mainly provided by IRAS, with resolutions of $\sim 30''\text{--}2'$.

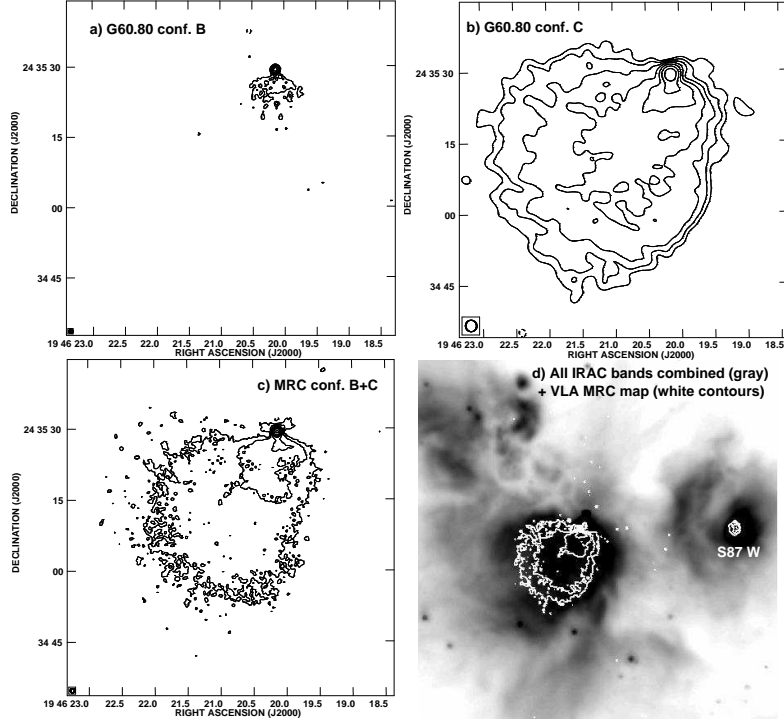


Fig. 1. The UC HII region with EE G60.88–0.13 (IRAS 19442+2427). a) and b) VLA images in configuration B (the UC emission) and configuration C (the EE). c) Combined VLA Multi-Resolution-Clean (MRC) map. This map strongly suggests a direct connection between the UC and the extended emission. d) All IRAC bands combined (gray) + VLA MRC map (white contours). Dust is predominant in the region. A spatial location agreement between dust and the HII region is observed.

Although the presence of large scale structures related to UC HII regions (Fig. 1b and 8c of [6]) had been inferred since 1967, the first interferometric surveys did not detect them. Nevertheless, their detection is possible with the VLA C and D configurations (e.g., [6]), albeit at the expense of resolution towards the UC emission (UCE). To mitigate these spatial filtering effects, we made multi-configuration VLA observations to provide a multi-scale view of the UC HII+EE (Fig.1c). Also, by using MSX observations, of higher resolution than IRAS, it is possible both to detect the EE and to resolve the UCE,

since the infrared observations are sensitive to the full range of angular sizes. The best IR satellite observations available for this purpose (see Fig. 1d) are from the Spitzer Space Telescope (<http://ssc.spitzer.caltech.edu>).

2 Energetics and Extended Emission

Comparing the total ionizing flux from the exciting star(s) calculated using RC and FIR observations, it is possible to analyze the energetics of the UC HII regions. The spectral type of the exciting star can be estimated in two ways: via the RC and via the IRAS fluxes. In the former case, the ionizing photon rate, N'_c , is estimated from VLA observations (eq. 1 of [2]) of the ionized gas. In the latter case, the total luminosity is measured via IRAS fluxes, and this luminosity is converted to an ionizing photon rate, N^*_c , using model stellar atmospheres (e.g., [7]; [8]). Both estimates consider an ionization-bounded, dust-free nebula. N'_c represents a lower limit to the spectral type because it is the minimum flux required to maintain the observed UC HII region; N^*_c represents an upper limit to the spectral type (for a single star producing L_{tot}).

A more realistic case is the presence of a stellar cluster and also of dust, as was considered by [1] and [2]. Assuming a spectral type for the most massive member of the cluster, and comparing it with the spectral type based on N'_c and N^*_c (Table 18 in [1] and Table 7 in [2]), they found that N^*_c (IRAS fluxes) and a single-star assumption resulted in the earliest estimate for the spectral type. The spectral type estimated from N'_c was always of somewhat later type. The spectral type derived for the most massive member of a cluster was roughly similar to that derived from the radio continuum. This suggests that there is a significant amount of dust in the regions, and many of the UV stellar photons do not contribute to the ionization but heat the dust instead.

Another important result is that the luminosity derived from IRAS suggests a much greater (earlier or more numerous) stellar presence than does the VLA luminosity. This *IR-excess* is quantified as $f_d = 1 - \xi = 1 - (N'_c / N^*_c)$, where f_d and ξ are the fraction of UV photons absorbed by dust and gas respectively. Values of $f_d \sim 1$ indicate a large IR-excess. Surveys by [1] and [2] found $0.42 < f_d < 0.99$ for 29 sources.

On the other hand, the presence of EE in a *direct connection* with the UC emission (i.e., a common structure of ionized gas embracing both emissions; see Fig. 1c and Fig. 3 of [5]) would significantly impact on our understanding of UC HII regions. It may imply that the definition, modeling, lifetime problem, and energetics of UC HII regions should be reconsidered. For example, as was pointed out in [6] and [5], if a direct connection is present, and if we consider a single ionizing star, the EE requires ~ 10 – 20 times more Lyman photons to maintain its ionization than the needed by the UCE. So, if the Lyman photons are underestimated in the N'_c determinations of [1] and [2], then the role of dust and the presence of clusters may have been over-estimated.

In light of the above, studies to understand and clarify the nature of the EE are needed. To date, only four efforts have been made.

2.1 The first three efforts

The first effort was made by Kurtz et al. (1999; [6]) with a sample of 15 UC HII regions. For 12 of them, they reported new, low-resolution VLA conf. D data at 3.6 cm (resolution of $9''$ and sensitivity to $9'$ structures). They contrasted these observations with those reported by [2] (conf. B at 3.6 cm, resolution $\sim 0.9''$; sensitivity to about $10\text{--}20''$) and the NVSS (conf. D at 20 cm, resolution $\sim 45''$; sensitivity to about $7\text{--}15'$). The aim was to detect a direct connection between the UCE and the EE, via a morphological study. If the UCE fits into a larger continuous structure, a direct connection could be possible. If a falloff in the emission to a near-zero value is observed between the UCE and the EE (a weak or null contour in the map), the direct connection could be unlikely. From the 15 fields, they found EE in 12, and evidence for a direct connection was present in eight. They calculate N'_c using the low-resolution VLA data and find that N'_c is similar to N^*_c .

The second effort was made by Kim & Koo (2001; [9]). This is based on a previous single-object (G5.48–0.24) study ([10]). They studied 16 sources with the VLA conf. DnC at 20 cm with resolution $\sim 30''$ and sensitivity up to $15'$. These observations included RC and $H76\alpha$, $He76\alpha$ radio-recombination lines (RRL's). They found EE in all sources, $H76\alpha$ in 15 and $He76\alpha$ in six. Based on the RRL data, they found similar LSR velocities in the UCE and EE, suggesting a direct connection between the two. They also present a theoretical model to explain the observed EE (density gradient in the molecular cloud plus a champagne flow).

The third effort was made by Ellingsen et al. (2005; [11]). They observed eight young (based on methanol maser emission) UC HII regions with the ATCA at 3.5 cm in the 750D configuration (resolution and sensitivity similar to VLA conf. D at 3.6 cm). In a similar way as [6], they contrasted their observations with other ATCA high resolution observations reported in the literature. They found EE with smaller sizes than the ones in the sample of [6], and explain that this effect may be due to a younger sample selected. Also, they support the theoretical model of [9].

2.2 A new effort using VLA, 2MASS, and IRAC (Spitzer)

The most recent effort was performed by de la Fuente ([12]) for a sample of 29 UC HII regions. The results will be published in a series of forthcoming papers. The aims were: (1) To complement and confirm the results and assumptions of [6] with a sample of 14 regions (12 from [6] plus G35.20–1.74 and G19.60–0.23); and (2) To explain how the presence of EE can affect the IR-excess (f_d), in the complete sample that includes 15 regions in [1] and [2]. Values of $f_d > 0.8$ were found for this UCE sample.

The methodology employed includes, when available, NIR (2MASS), MIR (IRAC [13] from the GLIMPSE program, <http://www.astro.wisc.edu/sirtf/>), and RC (VLA at 3.6 cm in configurations D, C, and B) observations. RC traces the ionized gas while NIR and MIR are good tracers of the stellar population and dust, respectively. With IRAC it is possible to detect dust and PAH emission at 3.6, 5.8 and 8.0 μm . Shocked gas can be observed through H_2 emission at 4.5 μm . The 3.6 μm (Spitzer) and the K_s (2.12 μm , 2MASS) images can show the presence of stellar clusters and nebulosities (ionized or reflection nebula). With IR photometry of these data, it is possible to identify the YSO population. Here, we summarize only the results regarding IRAC imagery and VLA maps.

Combining new VLA observations in conf. C with previous data in conf. B and D, a Multi-Resolution-Clean (MRC) map was created (e.g., Fig. 1c). If this map shows that the extended and UC emission form part of a continuous structure, then the suggestion of a direct connection is strong.

This behavior was confirmed in seven of the 14 regions in our sample. It was not seen in two (G33.13-0.09 and G48.61+0.02), and it is probable in five, although other observations (e.g., IRAC) are needed to confirm. In general, the results of [6] were confirmed for some of the sources, however, further observation and analysis is required for the others. For example, for G78.44+2.66 and G106.80+5.31, the MRC maps do not confirm a direct connection between the UCE and the EE (in agreement with [6]), nevertheless, the K_s image shows a nebulosity covering both emission regions. IRAC images (not currently available) could confirm the nature of the nebulosities.

Using new VLA conf. D observations at 3.6 cm for the 15 sources to complete the sample of 29, a determination of f_d was computed. Also in these new RC maps, EE is present in all sources. Based on their morphology, and following [6], a direct connection is also strongly suggested in 12 of the 15 regions. The cometary morphology was predominant in the whole sample. Confirming that the 29 sources present EE and IR-excess, a comparison between f_d (conf. D) and f_d (conf. B) was performed. For all sources, the presence of EE reduces the values of f_d . In summary, 10 regions have f_d (conf. D) ~ 0.2 , another 10 regions ~ 0.6 , and the other 9, ~ 0.7 .

The PAH emission is a good tracer of the “radiation temperature” and the IRAC 8 μm band is dominated by this emission (predominant at 7.7 μm). The striking comparison between the IRAC images and the VLA RC images (see Fig. 1d) suggests that the EE is due to ionizing radiation. However, soft UV radiation which may not significantly contribute to the overall HII region could be an important ionization source for the EE. In the 8.0 μm image, several knot-like sources are observed. They could be either star clusters or externally illuminated condensations. Furthermore, the 8.0 μm band can effectively trace weak structures and has proven useful in unveiling the underlying physical structure of the dense core/cloud (e. g., [14], [15]). Also, an agreement between the location of the RC emission peaks in the cometary arcs and the strongest emission in IRAC bands was observed.

In summary, the EE seems to be common in UC HII regions and is deserving of special attention in forthcoming studies and analysis. Multi-configuration VLA maps are critical to study morphologically the direct connection between UC HII regions and their associated EE. IRAC has been revealed as a powerful tool to study UC HII regions (with or without EE). The EE helps to explain the IR-excess observed because the N'_c calculated in [1] and [2] under-estimated the ionizing Lyman photons. Nevertheless, the over-estimation of dust in the regions is not necessarily true. On the other hand, in several sources the presence of clusters of stars in the UC HII+EE is inferred, in agreement with [2]. Hence, the assumptions of a single ionizing star and dust free nebula are not necessarily valid in the energetic studies.

3 The Aftermath

All the efforts are complementary, and individually none of them clarify the whole scenario. More studies are needed to clarify the nature, formation and evolution of the EE. A starting point is to standardize the observations (Molecular, HI, VLA multi-configuration, RRL's, and Spitzer) of all sources presented in these efforts. Combining these observations it is possible: 1) To confirm the validity of the model presented by [9]. 2) To measure the extinction. If similar extinction is measured in the UCE and EE, then it is possible to guarantee a direct relation between these components. This could be done by comparing NIR recombination lines with RC images. 3) To compare HI, RC, and IRAC observations looking for a relation between HII regions and PDR's.

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